Silicon Pixel Tracker (SPT) Update

Chris Damerell (RAL)

Reminder – why a new tracker concept?

- **Goal is to develop a tracking system of unprecedented transparency (~5% X_0) so that nearly all photons down to 7° θ_P will convert in the ECAL, and complications due to hadronic interactions in the tracker will be rare**

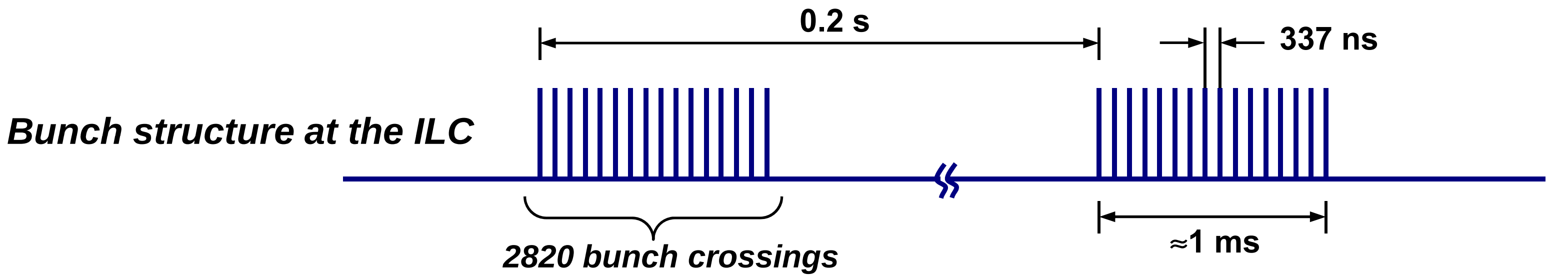
- **Maximise performance by using pixels, which provide unambiguous space points on each layer. 5 layers of closed barrels (with endcap disks) will provide considerable redundancy**

- **Maximise material transparency by allowing coarse timing information, since single-bunch timing will be provided by the ECAL. Basic principle is to strip out all feature that aren't strictly necessary, and which would increase the material in front of the calorimeter**

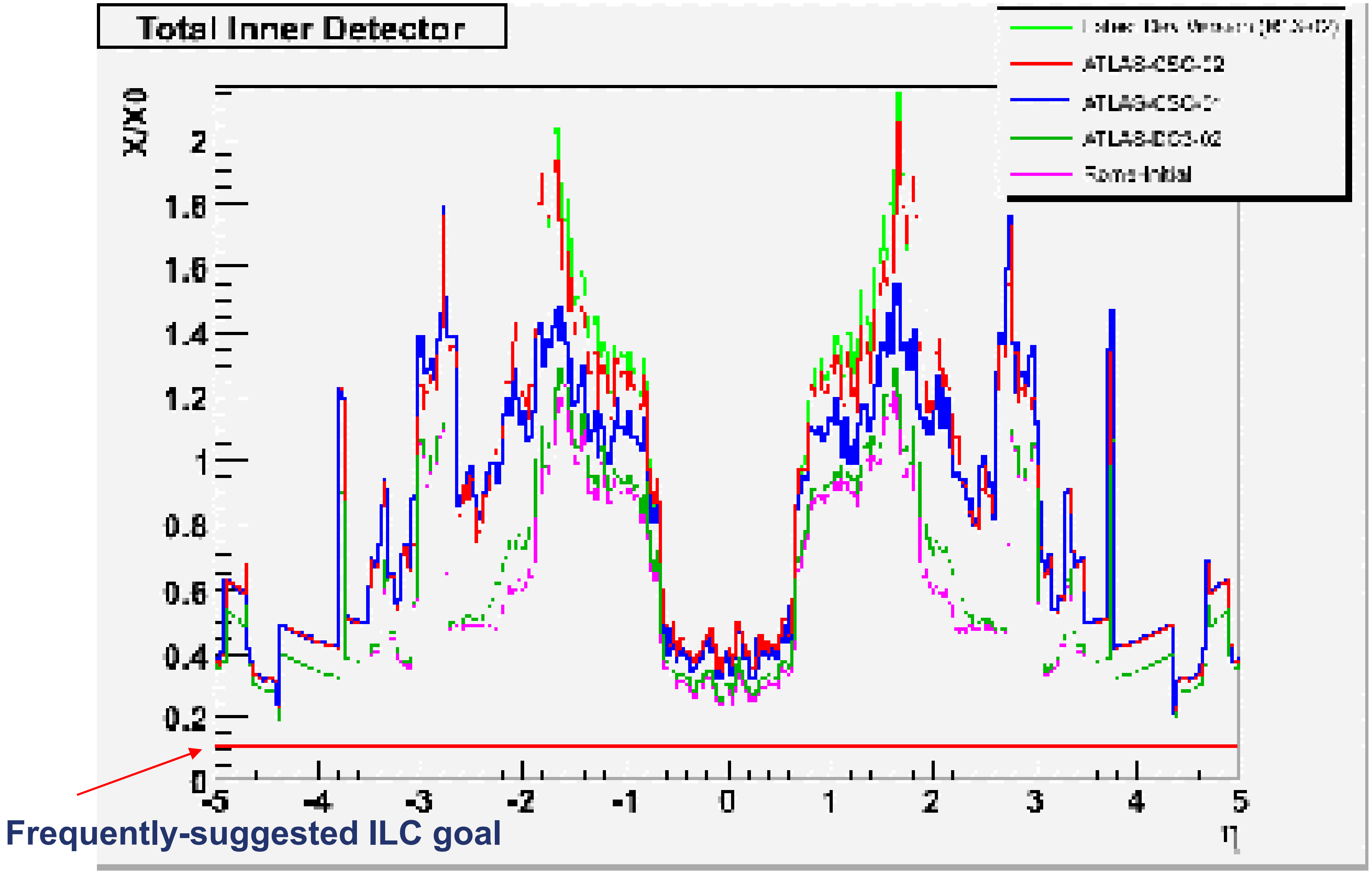
- **Advantages for physics will depend on detailed comparisons with the alternatives, once we have realistic material budget estimates for all options (including this one), all of which currently have large uncertainties**

- **Large prototypes should form part of the detector R&D programme, before tracking detector technologies are selected. Isn't there a risk that large flimsy structures may not be sufficiently stabie?**

- **This option is likely to be more expensive, but small compared with the calorimerty**



- Detector options:
  - Single bunch timing
  - Time-slicing of train (eg at 50 μs intervals, 20 slices of 150 bunches each)
  - Integrate signals through train, with relaxed readout during the inter-train period
- No 'right answer'. There may be a considerable advantage in time slicing or integration, namely *reduced power* Fine sensor granularity may compensate for pileup of background from multiple bunch crossings
- Lower peak power permits reduced cable plant, hence reduced material budget. Avoiding pulsed power has further electro-mechanical advantages
- There has been a successful history of exploiting tradeoffs between granularity and time resolution in ACCMOR and SLD vertex detectors
- Contrast LHC, where single bunch timing is mandatory, but one pays a heavy price in material …


Total Inner Detector
X/X0
ATLAS-CSC-02
ATLAS-DC3-02
Rome-Initial
η
Frequently-suggested ILC goal

- **We suggest that 5 layers of pixels (~50 μm) would have excellent standalone track reconstruction efficiency, even in the core of high energy jets, where 5 layers of single-sided unidirectional microstrips may be struggling**

- **Given PFA goals, there are clear advantages in robust standalone track-finding separately in the vertex detector and tracking systems**

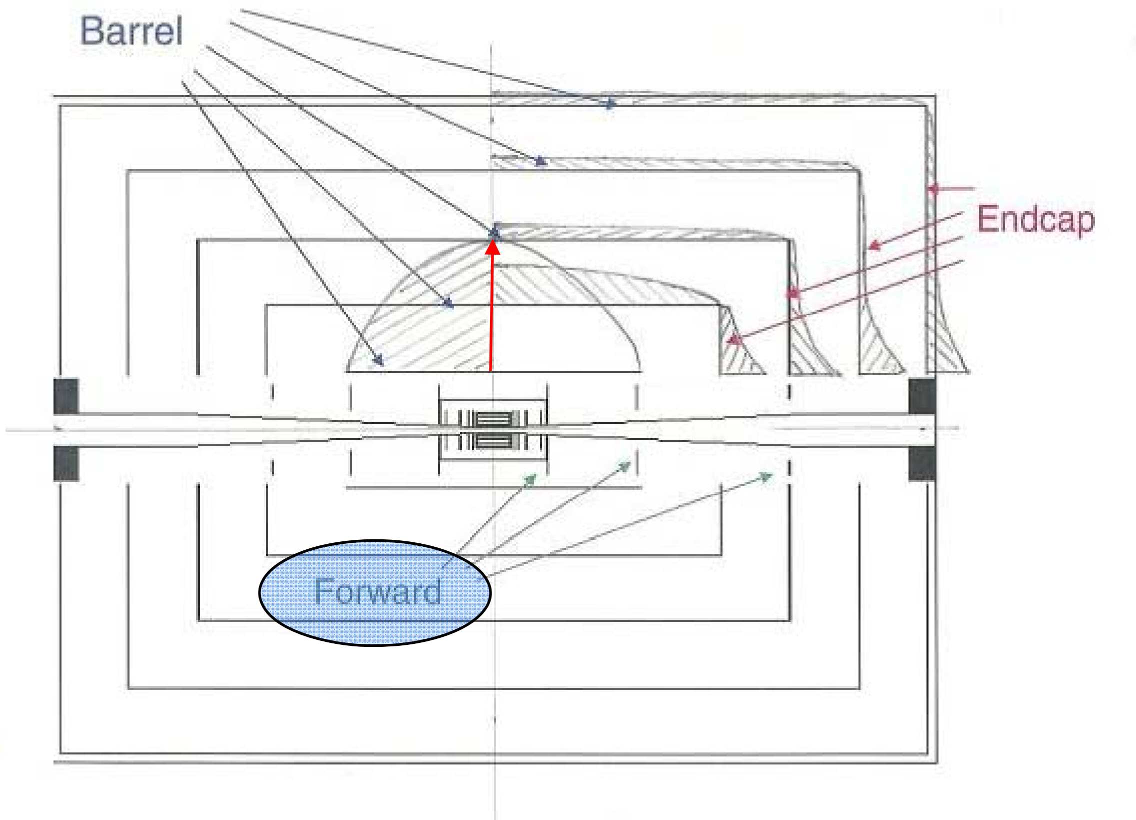
- **However, 'standard' MAPS devices would consume far too much power, so material budget would be blown away by the required cooling system**

- **If one can afford to integrate the background over 100 or so bunches, one can adopt an appropriate pixel technology, exchanging high pulsed power for low continuous power, with consequential benefit to material budget (cabling and mechanics)**

- **Integrating through the entire train causes no problems to the 'real' track finding: density of extra hits within a jet is negligible**

- **What is less clear is the impact on track finding of the salt-and-pepper background that populates the detector. Risk of an unacceptable load of fake tracks.**

- Total hit density ranges from 2.5/cm^2/train (layer 1 barrel) to 1/10 of that (layer 5 barrel) – occupancies in SPT are everywhere < 10^{-4}
- For the forward disks, densities exceed 600/cm^2/train, so pixels with short sensitive windows will be needed. Fortunately, area to be covered is small



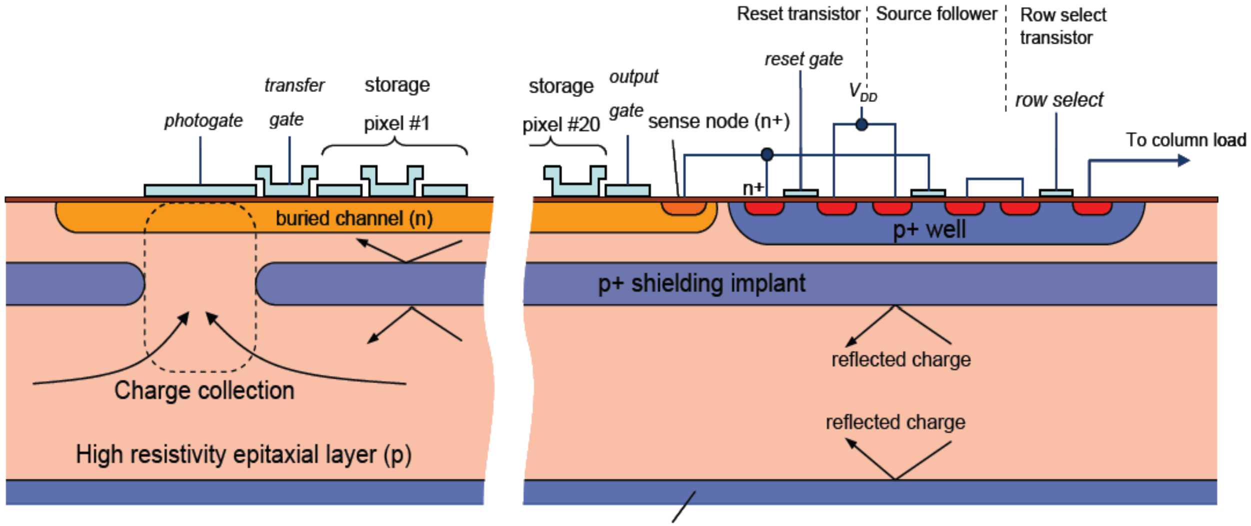
- **An outwards-to-inwards track finding procedure sketched in the Warsaw ILC workshop last June could provide robust standalone track-finding separately in the vertex detector and tracking systems**

- **Significant time-slicing through the train can be provided if necessary, with little overhead in power. Single-bunch time stamping is power hungry, but may be needed only at small radii (a small fraction of the tracker area)**

- **Some consideration was given to a CCD option, but the risk of severely damaging the detector in some radiatin accident may be too high**

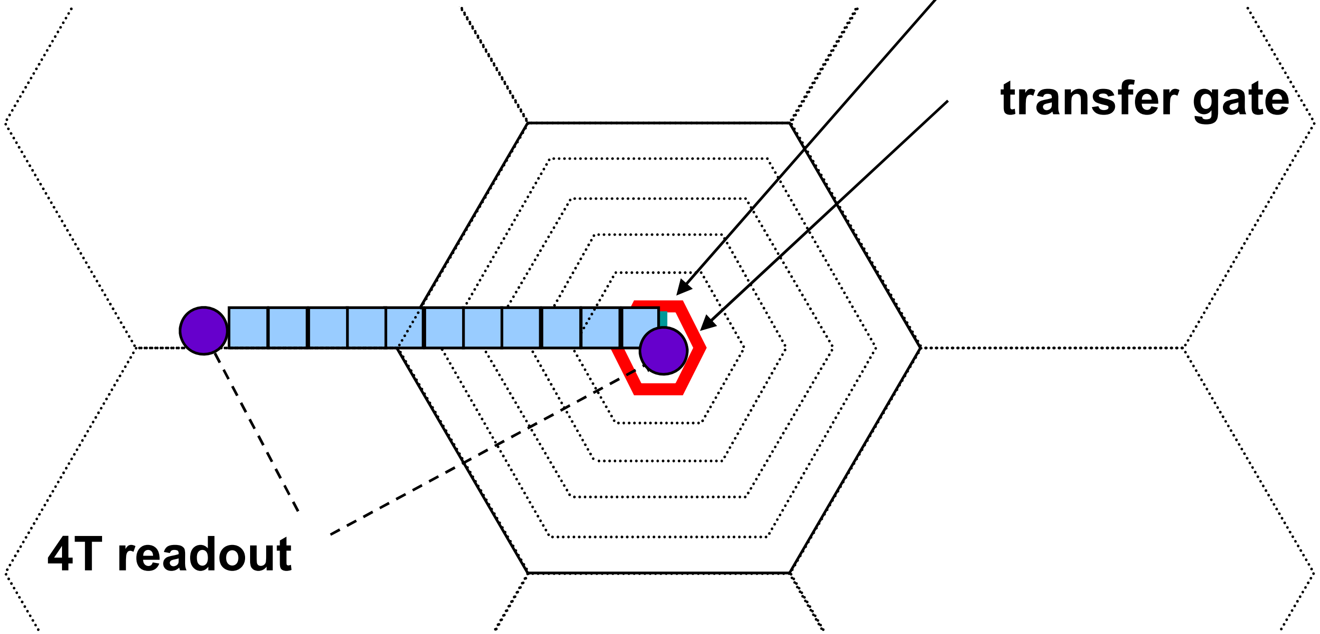
- **Currently looking at the ISIS architecture, which (depending on the number of time slices) is 100-1000 times more rad hard than the CCD**

- **ISIS is one of the strong candidates for ILC vertex detector, according to the review in Fermilab last October**



Operating principles of the ISIS:

- Charge collected under a photogate
- Charge is transferred to N-cell linear storage CCD in situ, N times during the 1 ms-long train
- Charge-voltage conversion and readout in the 200 ms-long quiet period after the train (insensitive to beam-related RF pickup)
- If structure can fit within say 5x80 μm, pixel pitch = 20 μm
- For SPT integrating through train, 50 μm pixels with binary readout will suffice
- Proof-of-principle ISIS-1 (e2V) demonstrated effective operation with x-rays; small-pixel version ISIS-2 is now delivered by Jazz Semiconductors
- Goal for vertexing is 20 storage cells with 20 μm square pixels; 100 cells (ie time slices) could easily be accommodated in a 50 μm pixel



SPT pixels (~50 μm diameter):

- 3 tiny transistors inside transfer gate in p-well, so shielding implant not needed
- ‘Deptuch funnel’ – need only ~50 mV per stage (and couldn’t be much more, with 0.18 μm 5 V process)
- Optional linear register for time slicing – this would need a shielding implant
- Both funnel and register have been done by e2V for confocal microscopy: 100% efficient for single photoelectrons – noiseless, by using LLL (L3) linear register

- **‘buried channel’ and ‘4T’ characteristics vary greatly between foundries – 1/f and RTS noise can be a big issue**

- **The term CDS is sometimes used loosely – beware of ‘frame-rate CDS’ which doesn’t offer pickup protection!**

Conclusions

- Silicon pixel tracker with signal integration through the bunch train, or up to some tens of time slices, based on ISIS principles, looks promising
- More slices could be implemented, without loss of radiation resistance, by evolving to a 3-D (vertically integrated) ISIS
- If it works, it should deliver a tracking system with extremely high performance and very little material in front of the calorimeter
- 50 Gpixels is ambitious, but similar technologies are already under development, for multi-Gigapixel focal plane arrays in astronomy (eg LSST)

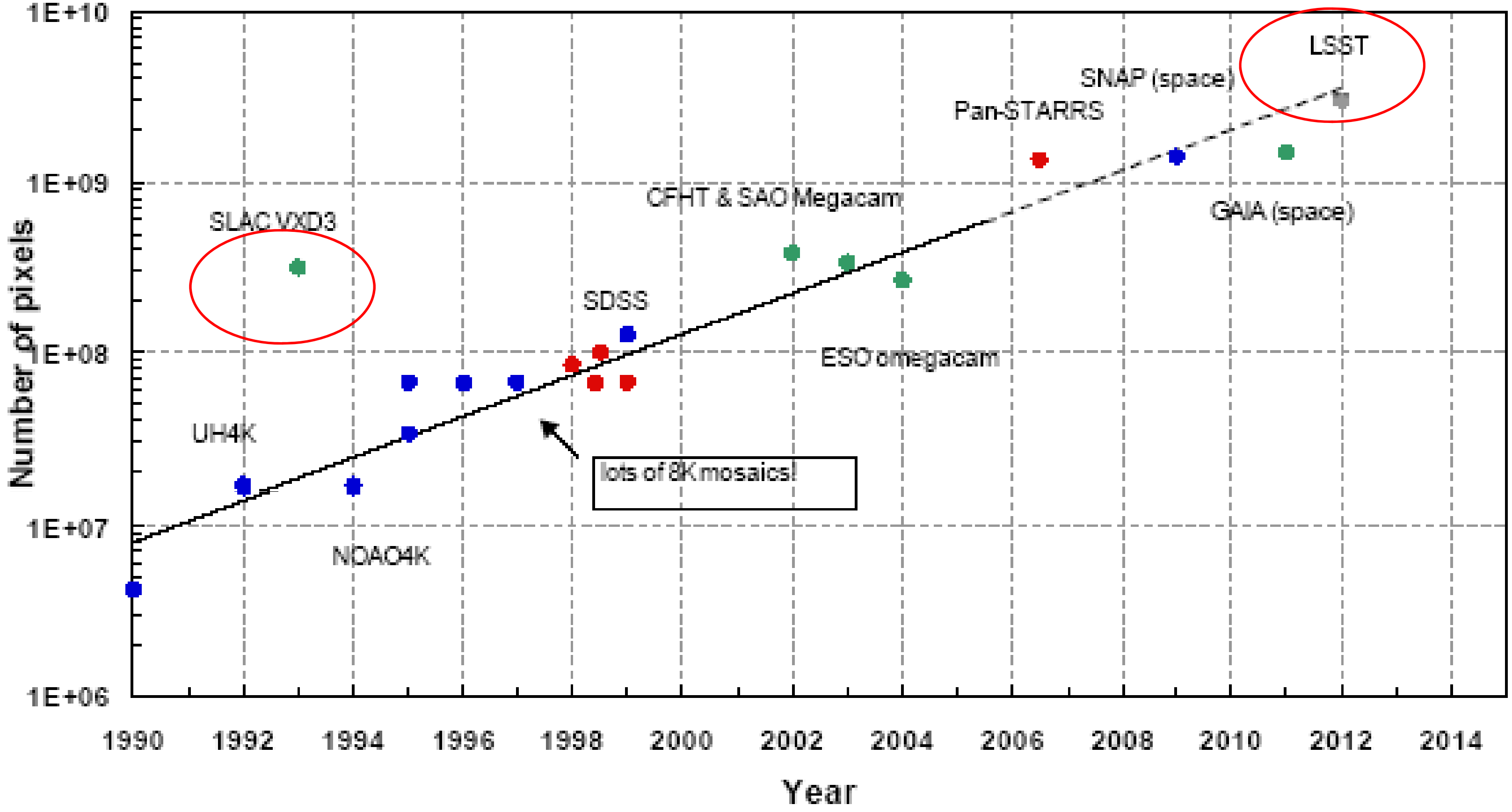
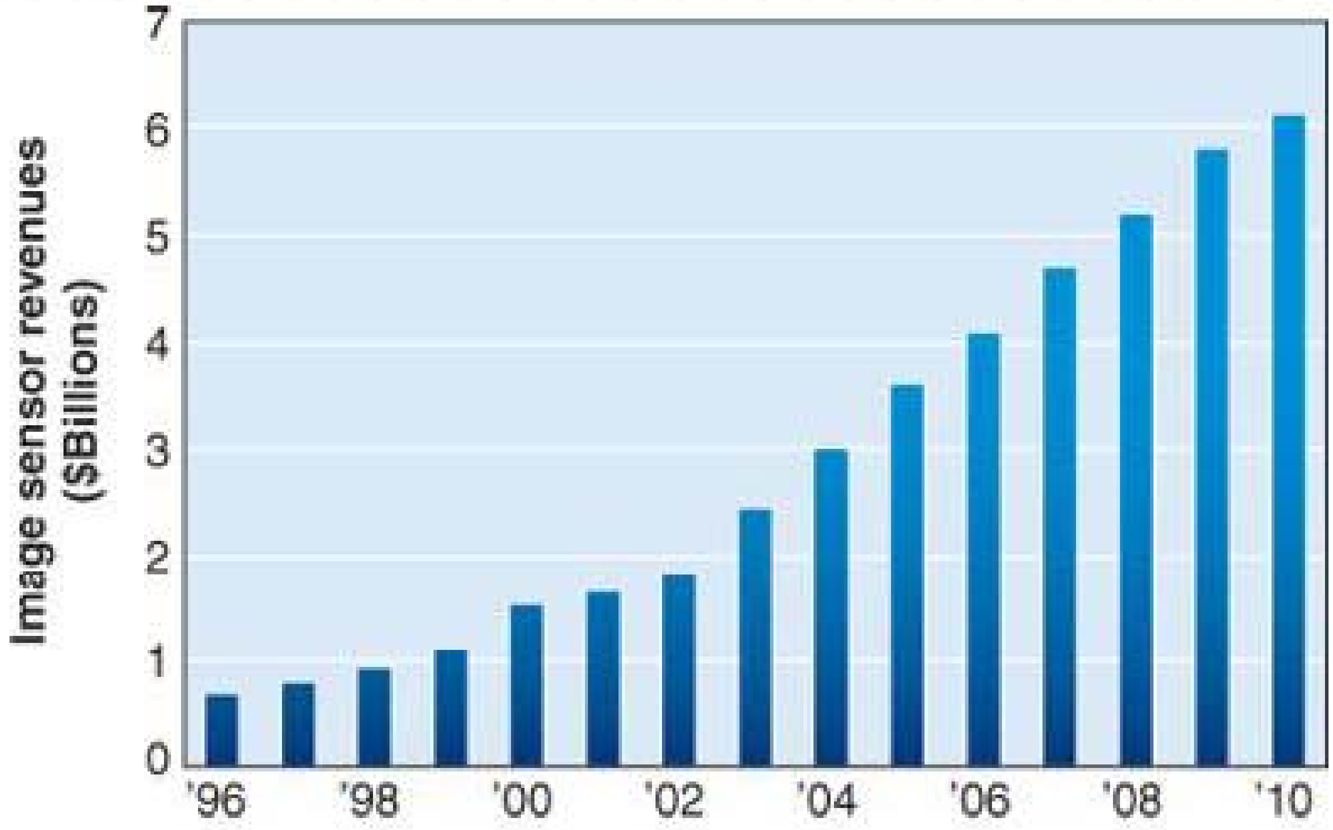


Illustration of focal plane sizes, from Luppino/Burke 'Moores' law

Focal plane size doubles every 2.5 years

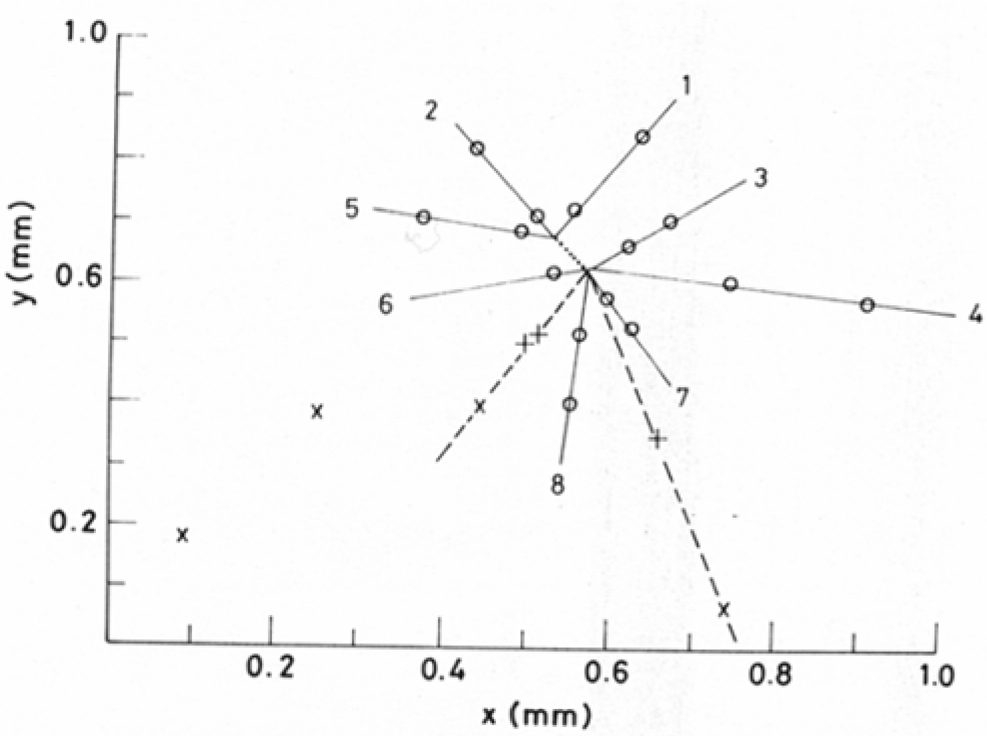
From: Burke, Jorden, Vu, SDW Taormina 2005

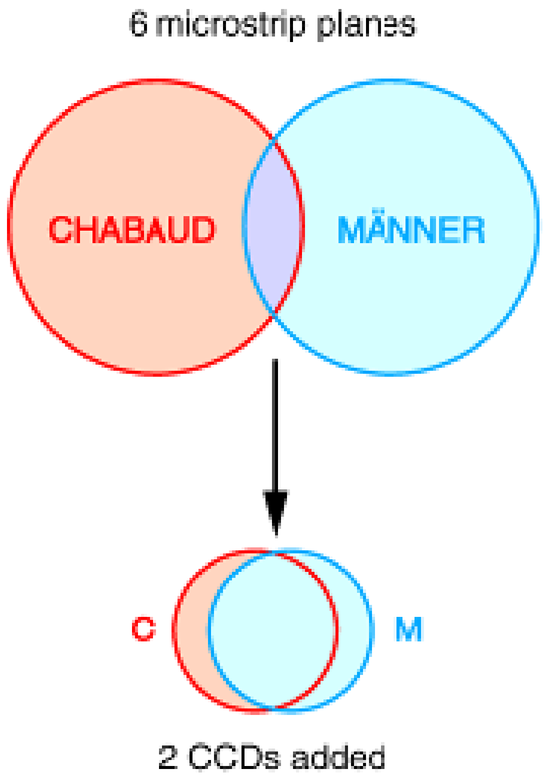


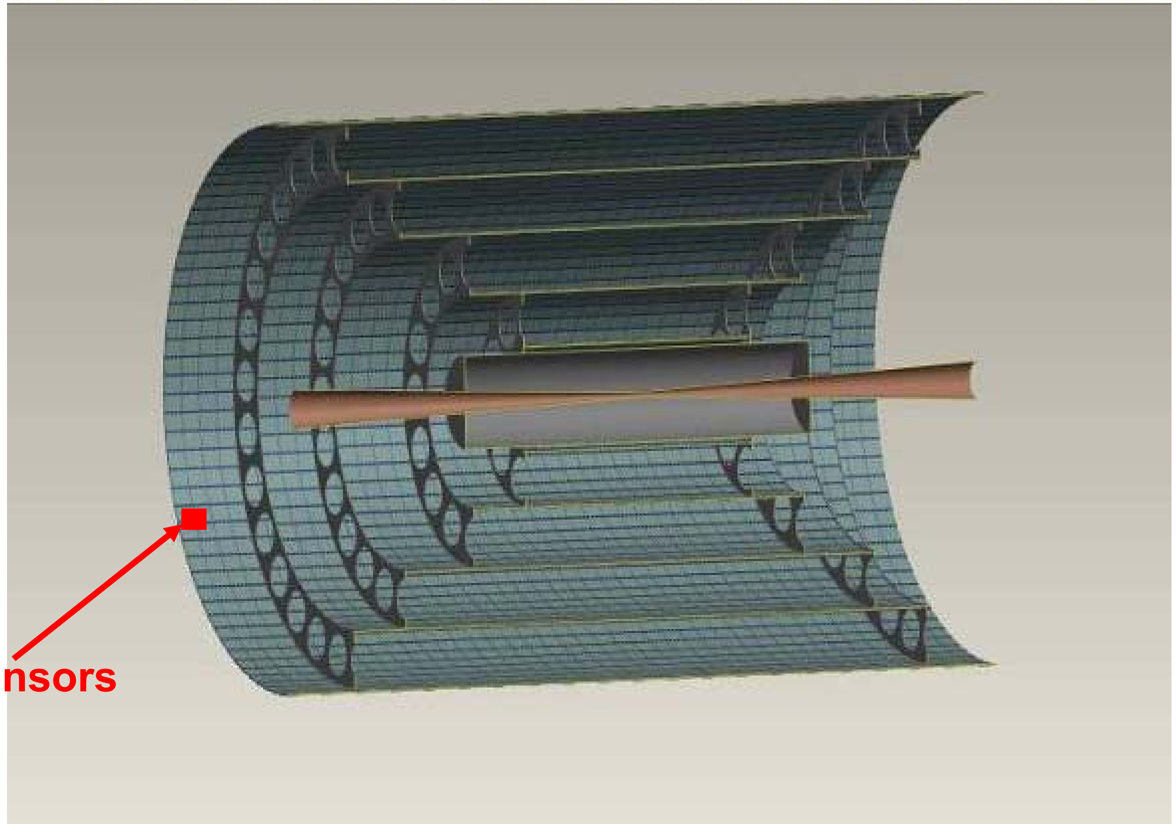
- As with developments in microelectronics, we particle physicists are small fish in a very large pond, in which the pace of developments is rapid
- Applications - digital cameras (still, video, phone cameras, …)

Backup

- A pixel tracker, being free of ghost hits, has a proven record for extremely high pattern recognition efficiency compared to microstrips, in high multiplicity jet-like events (ACCMOR Collaboration, mid-1980s)
- Total thickness of this standalone tracking system was 0.2% X_0

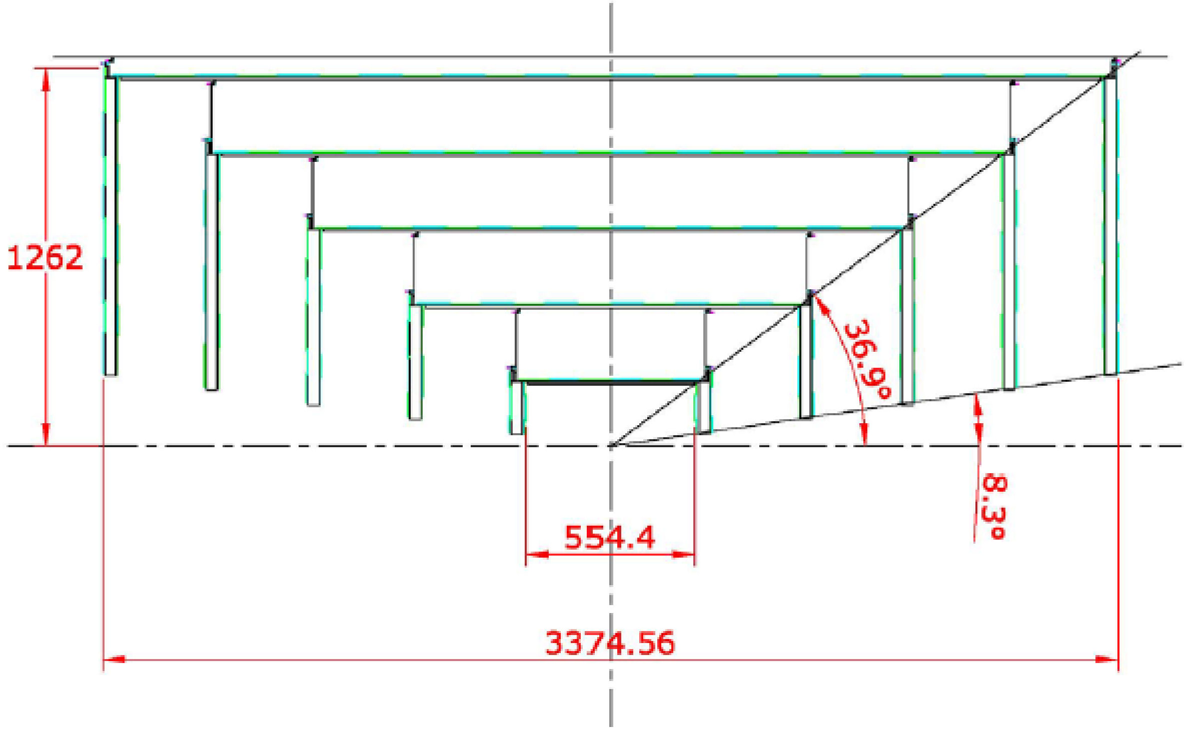






one of 11,000 sensors
8x8 cm^2

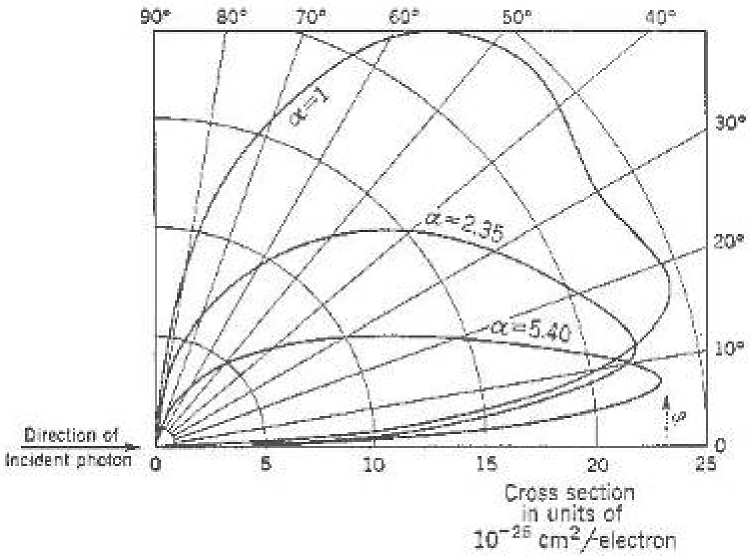
- SiC foam support ladders, linked mechanically to one another along their length
- 5 closed cylinders (incl endcaps, not shown) will have excellent mechanical stability
- ~0.6% X_0 per layer, 3.0% X_0 total, over full polar angle range, plus <1% X_0 from VXD system (goal)
- 30 Gpixels, in line with trends in astronomical wide-field focal plane systems by 2020



- Barrel and Forward trackers, total area = 70.3 m^2
- With 50 μm × 50 μm pixels – 28.1 Gpix system
- If each chip is 8 cm × 8 cm (2.6 Mpix): 11,000 sensors is total

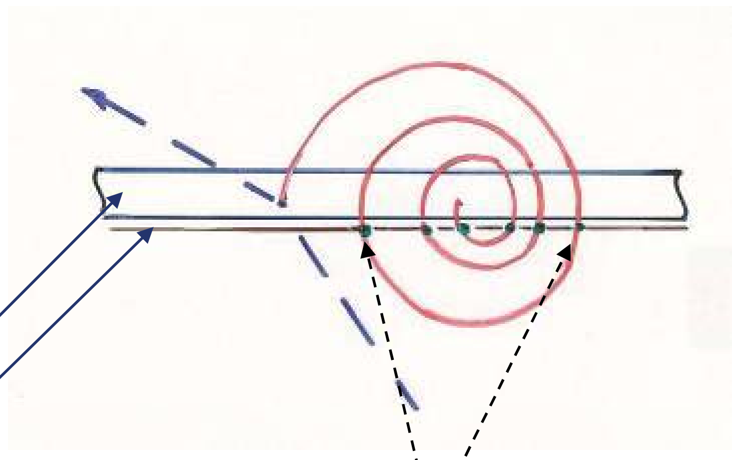
Backgrounds in silicon tracker

- Thanks to Takashi Maruyama, Norm Graf and John Jaros for help with this
- Takashi has calculated beamstrahlung-related and 2-photon backgrounds, both charged tracks and photon conversions
- 80% of hits are due to photons emitted from the BEAMCAL region, converting in the material of the tracker
- These photons are mostly of energy 0.1-1 MeV, with a peak at 0.51 MeV from positron annihilation in the BEAMCAL
- Using EGS, Takashi studied the conversion process in the detector, mostly Compton scattered electrons which generate typically 1-10 hits in a tracker layer, which he idealised as 300 μm Si. In our case, this probably over-estimates the effect, but not by much



Evans, p 691: photon energies 0.51, 1.2 and 2.76 MeV; electron angular distns

barrel ladder, rϕ view

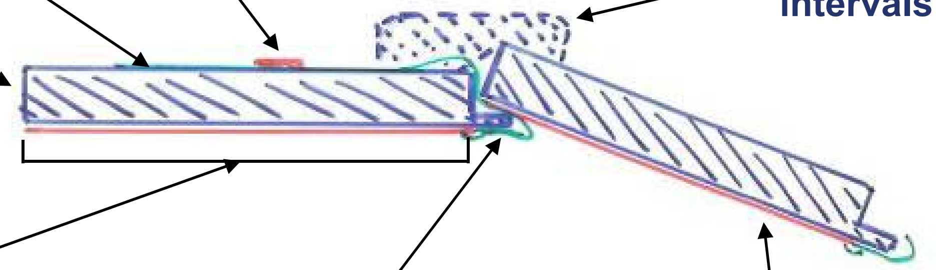


~0.5% X_0 support foam and Cu-kapton

~0.1% X_0 silicon, 30 μm active on inner surface

6 hits, stepped in z, each hit indistinguishable from min-I

End view of 2 barrel ladders ('spiral' geometry)



** single layer Cu/kapton stripline runs length of ladder, double layer in region of tabs (~5 mm wide) which contact each sensor. Single Cu/kapton stripline runs round the end of each barrel, servicing all ladders of that barrel

Bottom line: potential material budget ~0.6% X_0 per layer, but much design and R&D needed to establish mechanical stability, including shape stability wrt push-pull operations (taking advantage of stress-free 3-point kinematic mount)

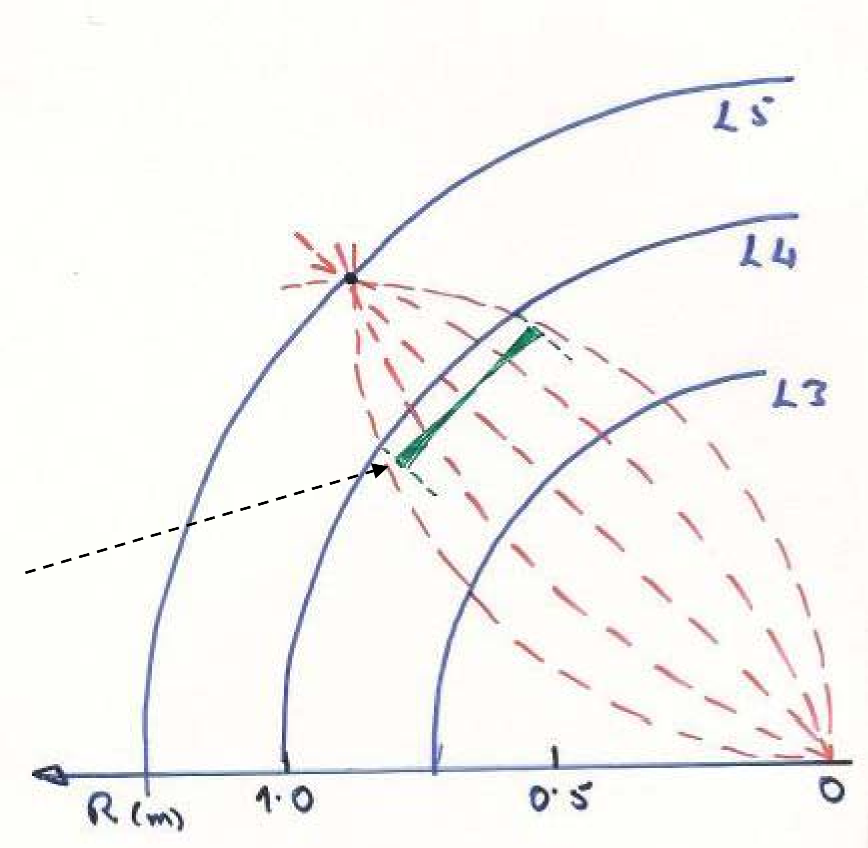
Possible track-finding strategy

- First deal with tracks having approximate IP constraint – prompt tracks and B and D decay products
- [Use Garfield approach for K-shorts and lambdas, as well as photon conversions and secondary interactions. A key point is that the latter will be considerably suppressed by the reduced material budget]
- Work from ‘outside’ in, where outside means seed layer 5, 4, 3, 2, 1, down to a p_T limit p_T(crit) for which track in r-ϕ view is at 45 degrees to the layer surface
- Layer p_T(crit) (GeV/c)

Layer	p_T(crit) (GeV/c)
5	1.33
4	1.05
3	0.77
2	0.49
1	0.21

- Particles with p_T below 200 MeV/c are to be found as curlers in the forward tracking detectors. This should be OK for those which originate within the VXD volume – but challenging for the small number born beyond (from long-lived B and D decays)

Search area on Layer 4



- Start with seed layer 5, and extrapolate each hit as a track candidate to layer 4, respecting the IP constraint and the p_T(crit) limit
- Multiple scattering implies a bow-tie profile for acceptable layer-4 links; +- 3 σ limit delivers on average 0.9 candidate tracks (looks pretty bad at this stage!)
- However, we can now extrapolate tracks of increasingly well-defined momentum to layer 3, 2, 1 with precision limited mainly by multiple scattering, and end up with well below 1 fake track per event, from 52000 seeds in layer 5

- Extrapolation outwards to ECAL cleans up the fake tracks, plus the out-of-time background charged particles, which mostly come from 2-photon background
- This step won't be perfect – a fake track may point to a genuine ECAL cluster, but we appear to be talking about cleanup of a small number of fakes, and a matching ECAL cluster does need to be charged and compatible both in position and direction with the track candidate
- Procedure becomes less beautiful as seed layer is stepped inwards to pick up lower-p_T tracks, but even the lowest momentum particles end up in the forward ECAL for validation, so this approach probably remains robust
- Same procedure works for the endcap disks, with p_T(crit) defined by the radial position of the seed hit. Multiple scattering effects are generally reduced (fewer cases of extreme obliquity)

Technology options

- Conventional CCDs can be used wherever full train integration is permissible. Availability of 30 Gpixel system with 8x8 cm^2 devices on timescale of 2020 is assured – driven by dark energy and other wide-field camera systems in astronomy

- Cost is expected to be ~$30M, far higher than microstrips, so a serious performance comparison (particularly of PFA) will be needed before carrying this forward

- If finer time slicing is required (10 to 100 sensitive windows per train) the ISIS technology looks promising. Availability and yield of 8x8 cm^2 devices is not yet established, but there is time enough for that

- With either option, slowly step through all 11000 devices ladder by ladder for relaxed readout of undisturbed signal charge from up to 100 time slices during the 200 ms, with low and constant power dissipation. Estimate for the CCD option is 600 W total power, dissipated steadily while running – well within the capability of gentle gas cooling